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ABSTRACT

This multidisciplinary research project was concerned with the development, understanding and application of powerful techniques for the manipulation and study of spin systems, the fabrication and study of interacting spin assemblies, and the study, characterization and application of spin transfer effects and of nanomagnet dynamics excited by spin polarized currents. Major accomplishments achieved during this project include the development and application of new tools and innovative techniques for the manipulation and study of spin phenomena in semiconductor systems, and other spintronics materials of technological importance, and the spectroscopic study of the spin transport properties of nanoscale systems, the demonstration of terahertz spin control in magnetic semiconductor quantum wells, the study of spin transport in single molecule devices, and the manipulation and successful study and understanding of individual spin-spin interactions in semiconductor surfaces. Major advances were also made in the understanding, development and enhancement of methods for the spin-transfer switching of nanomagnets for high density current addressable MRAM applications, and in the understanding and development of nanomagnet microwave oscillators for future information processing applications.

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(a) Papers published in peer-reviewed journals (N/A for none)

1. “Magnetic Anisotropy Variations and Nonequilibrium Tunneling in a Cobalt Nanoparticle,” M. M. Deshmukh, S. Kleff, S. Guéron, E. Bonet, A. N. Pasupathy, J. von Delft, and D. C. Ralph, Phys. Rev. Lett. 87, 226801 (2001).

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(c) Presentations

1. "Manipulation of Quantum Information with Semiconductor Spintronics", D. D. Awschalom, Conference on Quantum Information, Institute for Theoretical Physics, University of California, Santa Barbara, CA, December 3-7, 2001.

2. "Spintronics and Quantum Information Processing in Semiconductor Nanostructures," D. D. Awschalom, Fall Meeting of the Materials Research Society, Boston, MA, November 26-30, 2001.

3. "Electron Spin Coherence in Ferromagnetic/Semiconductor Heterostructures," D. D. Awschalom, 46th Annual Conference on Magnetism and Magnetic Materials (MMM 2001), Seattle, WA, November 12-16, 2001.

4. "Multifunctional Spintronics and Quantum Information Processing in Semiconductors," D. D. Awschalom, Computer Systems Laboratory Colloquium, Stanford University, Stanford, CA, October 24, 2001.

5. "Semiconductor Spintronics and Coherence Spin Dynamics," D. D. Awschalom, 12th International Conference on Hot Carriers in Semiconductors, Santa Fe, NM, August 27-31, 2001.

6. “Spin Transfer Effects in Magnetic Nanopillars,” Robert A. Buhrman, Fall Meeting of Materials Research Society, Boston, MA, November 26-30, 2001.

7. “Spin-dependent Transport in Magnetic Nanostructures,” Robert A. Buhrman, Workshop on Ferromagnetic-Semiconductor Nanostructures, July 23 - 26, 2001 Regensburg, Germany.

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9. “Theory of Ultrafast Manipulation of Electron Spin in Semiconductor Quantum Dots,” C. Pryor and M. E. Flatté, March Meeting of the APS, March 18, 2002

10. “Torques from Spin-Polarized Currents,” D. C. Ralph, Aspen Institute for Physics Workshop, Aug. 7, 2001, Aspen, CO

11. “Spins and Interactions in Metal Nanostructures,” D. C. Ralph, Nanoscience Conference Aug. 20-24, 2001, ITP, Santa Barbara, CA

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13. "Torques and Tunneling in Nanomagnets," D. C. Ralph, 15th International Vacuum Conference / American Vacuum Society International Symposium, Oct. 28-Nov. 1, 2001, San Francisco, CA

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17. “MRFM: A Sensitive Local Probe for Spin Electronics”, M. L. Roukes, The First International Conference and School on Spintronics and Quantum Information Technology (SPINTECH-1), May 13-18, 2001, Maui, Hawaii.

18. “Nanoscale Systems for Information Technologies,” R. A. Buhrman, National Nanotechnology Initiative: From Vision to Accomplishments Conference, Washington, D.C. April 29-May 1, 2002.

19. “Spin transfer effects in magnetic nanostructues,” R. A. Buhrman, LATSIS 2002 Symposium, Lausanne Switzerland, June 4-6, 2002.

20. “Spin-Transfer Phenomena and Spin-Dependent Transport in Magnetic Nanostructures,” R. A. Buhrman, ICTP Conference on The Science and Technology of Spins in Nanostructures, Trieste, Italy, August 19-22, 2002.

21. “Spin Gating and Nuclear Imprinting in Semiconductor Nanostructures,” D. D. Awschalom, Conference on Recent Highlights in the Nanoworld, Joint CNSI/CENS/Biozentrum Basel Workshop, Wildbad Kreuth, Germany, October 6-9, 2002.

22. “Ferromagnetic Imprinting of Nuclear Spins in Semiconductors,” R. K. Kawakami (and D. D. Awschalom), 2nd International Conference on the Physics and Applications of Spin-related Phenomena in Semiconductors, Wurzburg, Germany, July 23-26, 2002.

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30. “Ferromagnetic Imprinting of Nuclear Spins in Semiconductor Heterostructures,” D. D. Awschalom, Materials Research Society National Spring Meeting, San Francisco, CA, April 1-5, 2002.

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New York

40. “Manipulating Nanomagnets with Spin-Polarized Currents,” D. C. Ralph, Tutorial Session at the Fall MRS Meeting: MagnetoElectronics and Novel Magnetic Phenomena in Nanostructures, December 1, 2002, Boston, MA

41. “Theory of Spin Coherence in Semiconductors,” M. E. Flatté, Rank Prize Fund Symposium on Optical Orientation and Spintronics, United Kingdom, March 18-20, 2002.

42. “Theory of Ultrafast Electron Spin Manipulation in Quantum Dots,” C. Pryor and M. E. Flatté, March Meeting of the American Physical Society, Indianapolis, IN, March 18, 2002.

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45. “Manipulating Nanomagnets with Spin-Polarized Currents,” D. C. Ralph, 12th Advanced Photon Source User Meeting, workshop: Nanoscience, Controlling Interactions in Complex Materials, May 1, 2003, Argonne National Laboratory.

46. “Quantum States in Metal Nanoparticles and Single Molecules,” D. C. Ralph, Gordon Research Conference on Condensed Matter Physics, June 22-27, 2003, Connecticut College.

47. Lecturer at the Boulder School for Condensed Matter and Materials Physics: Frontiers in Magnetism, July 11-16, 2003, Boulder, CO
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    Lecture 1: Torques from Spin-Polarized Currents
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    Lecture 3: Coulomb Blockade and Tunneling in Small Magnets

48. “Tools for Molecular Spintronics,” D. C. Ralph, SPINS/Spintronics Review, Oct. 13-16, 2004, Santa Monica, CA

49. “Nano-Processing and Properties of Spin Transfer Device Structures”, R. A. Buhrman, Intermag 2003, Boston. March 31 – April 3, 2003.

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55. “Spintronics Reloaded: Semiconductors, Molecules, and Quantum Information Processing,” D. D. Awschalom, Symposium on Functional Electronic Materials: Key to New Science and Technology, Washington, DC, October 3, 2003.

56. “Gigahertz Manipulation of Electron Spins in Semiconductor Nanostructures,” D. D. Awschalom, Plenary Speaker, 36th International Symposium on Compound Semiconductors, San Diego, CA, August 25-27, 2003.

57. “Spin Coherence in Semiconductors,” D. D. Awschalom, SPINTECH II, International Conference and School on Semiconductor Spintronics and Quantum Information Technology, Brugge, Belgium, August 4-8, 2003.

58. “Optoelectronic Control of Electron and Nuclear Spins in Semiconductors,” D. D. Awschalom, Symposium on Spin Dynamics in Semiconductors, International Conference on Magnetism, Rome, Italy, July 27 – August 1, 2003.

59. “Manipulation of Quantum Information with Semiconductor Spintronics,” D. D. Awschalom, Plenary Prize Lecture, International Conference on Magnetism, Rome, Italy, July 27, 2003.

60. “Manipulation and Control of Spins in Semiconductors,” D. D. Awschalom, UCSB-Los Alamos National Laboratory Workshop, Kavli Institute for Theoretical Physics, Santa Barbara, CA, June 3, 2003.

61. “Optoelectronic Control of Electron and Nuclear Spins in Nanostructures,” D. D. Awschalom, Quantum Electronics and Laser Science Conference (QELS-3), Baltimore, MD, June 1-6, 2003.

62. “Spin Control and Engineering in Semiconductors,” D. D. Awschalom, Components Research Forum, Intel Corporation, Hillsboro, OR, May 27, 2003.

63. “Manipulating Spins in Semiconductors for Quantum Information Processing,” D. D. Awschalom, Conference on Glasses and Disorder, Kavli Institute for Theoretical Physics, Santa Barbara, CA, May 19-23, 2003.

64. “Optoelectronic Control of Electron and Nuclear Spins in Semiconductor Nanostructures,” D. D. Awschalom, Condensed Matter Seminar, University of Iowa, Iowa City, IA, April 8, 2003.

65. “Spintronics for Logic, Storage, and Computing,” D. D. Awschalom, Department of Defense Advisory Group on Electron Devices (AGED) and Microelectronics, Special Technology Area Review on Spintronics, Santa Barbara, CA, March 19, 2003.

66. Plenary Lecture on Spintronics, D. D. Awschalom, International Symposium on “Carrier Interactions and Spintronics in Nanostructures,” (CISN2003), NTT Atsugi R&D Center, Japan, March 10-12, 2003.

67. “Spintronics and Quantum Information in Semiconductors,” D. D. Awschalom, Keynote Presentation, 2003 International Nanotechnology Conference (Nanotech 2003), San Francisco, CA, February 23-27, 2003.

68. “Manipulating Quantum Information with Semiconductor Spintronics,” D. D. Awschalom, Cooper Symposium, Physics and Chemistry of Semiconductors and Interfaces, Salt Lake City, UT, January 19-23, 2003.

69. “Nanoelectronics Theory”, M. E. Flatté, Nanoscience and Technology Symposium, Iowa City, IA, November 12, 2003.

70. “Future Issues in Spintronic Materials”, M. E. Flatté, American Vacuum Society 50th International Symposium, Baltimore, MD, November 5, 2003.

71. “Molecular Beam Epitaxy for Quantum Information Processing”, M. E. Flatté, North American Molecular Beam Epitaxy Conference, Keystone, CO, October 2, 2003.

72. “Optical and Electrical Manipulation of Spin Orientation in Compound Semiconductors”, M. E. Flatté, W. H. Lau, C. E. Pryor, and I. Tifrea, International Symposium on Compound Semiconductors 2003, San Diego, August 25, 2003.

73. “Spin Dynamics in Semiconductors”, M. E. Flatté, SPINTECH II: 2nd International Conference and School on Spintronic and Quantum Information Technology, Brugge, Belgium, August 7, 2003.

74. “Ballistic Magnetoresistance in Stable Ferromagnetic Contacts,” R. A. Buhrman, Invited paper presented at Special Symposium on Ballistic Magnetoresistance, 9th Joint Magnetism and Magnetic Materials/Intermag Conference, Jan. 5-9, 2004, Anaheim, CA

75. “Spin Transport and Spin Transfer Effects in Magnetic Nanostructure,” R. A. Buhrman, Invited lecture presented at Tutorial on Magnetoelectronic Transport, March Meeting of the American Physical Society, March 22-26, 2004, Montreal, Canada

76. “Applying Torques to Magnets Using Spin-Polarized Currents,” D. C. Ralph, Special Tutorial Session on Spintronics, 9th Joint Magnetism and Magnetic Materials/Intermag Conference, Jan. 5, 2004, Anaheim, CA

77. “Manipulating Nanomagnets with Spin-Transfer Torques,” D. C. Ralph, Aspen Winter Conference: “Spins in Nanostructures: From Atoms and Quantum Dots to Magnets” Jan. 6-10, 2004, Aspen Center for Physics, Aspen, CO

78. “Spins in Metal Nanostructures and Molecular Devices,” D. C. Ralph, Moriond Conference on Mesoscopic Physics, Jan. 25-Feb. 1, 2004, La Thuile, Italy

79. “Nano-Science and Technology: A Progress Report,” D. C. Ralph, University of Iowa Physics Department Public Lecture Series, April 12, 2004, Iowa City, Iowa

80. “Spin-Transfer-Driven Magnetic Switching and Precession,” D. C. Ralph, CNS Nanotechnology Symposium: “Nanomagnetics – From Discovery to Systems” May 14, 2004, Ithaca, NY

81. Lectures at the Les Houches Summer School of Theoretical Physics “Nanoscopic Quantum Physics,” D. C. Ralph, June 28-July 30, 2004, Les Houches, France

Lecture 1: A Pictorial Introduction to Coulomb Blockade and Quantum Dots
Lecture 2: Spin-Orbit Interactions and a Universal Hamiltonian for Electron- Electron Interactions
Lecture 3: Magnetism and Superconductivity in Quantum Dots
Lecture 4: Spin-Transfer Torques on Nanomagnets
Lecture 5: Tools for Molecular Electronics

82. “Manipulating Nanomagnets Using Spin-Polarized Currents,” D. C. Ralph, The 3rd International Conference on Physics and Applications of Spin-Related Phenomena in Semiconductors (PASPS III), July 21-23, 2004, Santa Barbara, CA

83. “Microwave Oscillations of a Nanomagnet Driven by a Spin-Polarized Current,” S. I. Kiselev, Invited paper presented at 9th Joint Magnetism and Magnetic Materials/Intermag Conference, Jan. 5-9, 2004, Anaheim, CA

84. "Dynamics of nanomagnets driven by spin polarized currents,” I. N. Krivorotov, Invited paper presented at 5th International Symposium on Metallic Multilayers, June 7-11, 2004, Boulder, Colorado

85. “Microwave Oscillations of a Nanomagnet Driven by a DC Spin-Polarized Current,”S. I. Kiselev, Invited paper presented at the March Meeting of the American Physical Society, March 22-26, 2004, Montreal, Canada

86. “Metal-nanoparticle single-electron transistors fabricated using electromigration,” K. I. Bolotin, Invited paper presented at March Meeting of the American Physical Society, March 22-26, 2004, Montreal, Canada

87. “Probing single spin orientation with scanning tunneling microscopy in GaMnAs” J. M. Tang and M. E. Flatté, selected talk presented at PASPS-3, Santa Barbara, July 2004.

88. “Nonlinear spin transport and gain in semiconductors,” M. E. Flatté, Invited talk presented at PASPS-3, Santa Barbara, CA July, 2004

89. “Ferromagnetic Resonance Force Microscopy”, P. Wigen, Invited paper presented at Second Seeheim Conference on Magnetism, SCM-2004 June 27-July1, 2004, Seeheim, Germany

90. “Ferromagnetic Resonance Force Microscopy,” P. Wigen, Invited Lecture presented at School on Nanostructured Systems: Basic Properties and Technology, Bedlewo, Poland, 31st May to 2nd June 2004

91. “Spin-spin interactions on semiconductor surfaces,” A. Yazdani, Invited paper presented at Aspen Center for Physics: Winter Conference on Condensed Matter, Aspen, January 2004.

92. “Tools for Molecular Electronics, ” D. C. Ralph ,invited talk presented at International Symposium on Bio-Conjugated Materials and Molecular Devices, Dec. 6-8, 2004, Ithaca, NY

93. “Electron and Spin Transport in Single-Molecule Transistors,” D. C. Ralph, invited lecture presented by at 2005 Electrochemistry Gordon Research Conference, February 20-25, 2005, Ventura, CA

94. “Tools for Studying Electron and Spin Transport in Single Molecules,” D. C. Ralph, invited talk presented at 2003 March Meeting of the American Physical Society, March 21-25, 2005, Los Angeles, CA

95. “Manipulating Nanomagnets with Spin-Polarized Currents” D. C. Ralph, invited lecture presented at “Current Topics in Micromagnetics” Workshop, June 1-3, 2005, the Courant Institute, NYU, New York, NY

96. “Transport in Metal and Molecular Nanostructures,” Lectures at the Boulder School for Condensed Matter and Materials Physics: Mesoscopic Physics, July 4-22, 2005, Boulder, CO, D. C. Ralph, Lecture titles:

Lecture 1: Introduction to Coulomb Blockade and Energy Levels in Quantum Dots
Lecture 2: Interacting Electrons inside Quantum Dots
Lecture 3: Review of Kondo Experiments and Molecular Electronics
Lecture 4: Nano-Magnetics and Spin-Transfer Torques

97. “Spin Transfer and Spin Transport in Magnetic Nanostructures”, R. A. Buhrman, invited lecture presented at Magnetic Nanostructures Gordon Conference, Big Sky, MT, August 24-27, 2004.

98. “Tutorial on Fabrication and Properties of Magnetic Nanostructures,” R. A. Buhrman, presented at MRS Meeting, Boston MA, Nov. 28, 2004.

99. “Spin Torque Effects in Magnetic Nanostructures,” R. A. Buhrman, invited talk at MRS Meeting, Boston MA, Nov. 30, 2004.

100. “Mn in GaAs studied by X-STM: from a single impurity to ferromagnetic layers”, A. M. Yakunin, A. Yu. Silov, P. M. Koenraad, J. H. Wolter, J.-M. Tang, M. E. Flatté, A. M. Monakhov, K. S. Romanov, I. E. Panaiotti, N. S. Averkiev, W. Van Roy, J.-L. Primus, J. De Boeck, D. Kolovos, L. Däweritz, and K. H. Ploog, invited talk, 12th International Conference on Modulated Semiconductor Structures, Albuquerque, New Mexico, July 10-15, 2005.

101. “Unipolar and Bipolar Spin Transistors”, M. E. Flatté, invited talk, 63rd Device Research Conference, Santa Barbara, California, June 21, 2005

102. “Probing single spin resonances with scanning tunneling microscopy”, J.-M. Tang and M. E. Flatté, invited talk, 49th Annual Conference on Magnetism and Magnetic Materials, Jacksonville, FL, Nov. 7-11, 2004.

103. “Theory of the electron g-factor and spin decoherence in semiconductors”, M. E. Flatté and W. H. Lau, invited talk, Colorado Meeting on Fundamental Optical Properties of Semiconductors, Estes Park, CO, August 10, 2004.

104. “Spin-spin interactions on semiconductor surfaces,” A. Yazdani, invited presentation at Max-Planck-Institute Dresden workshop on "Nanoscale Fluctuations in Magnetic and Superconducting Systems (NANO05)", Dresden, Germany, May 2005.

105. “Interaction between Isolated Mn Acceptors on GaAs surfaces,” A. Yazdani, invited presentation at Frontiers of Science within Nanotechnology conference, Boston University, August, 2005.

106. "Spintronics and Nanomagnetics", D.D. Awschalom, Plenary Lecture, International Conference on Nanotechnology and New Materials (NANOMAT), Bergen, Norway, June 6-7, 2007.

107. “Generating Spin Currents in Semiconductors with the Spin Hall Effect,” V. Sih (and D.D. Awschalom), 10th Joint MMM/Intermag Conference, Baltimore, MD, January 7 - 11, 2007.

108. “Manipulating and Coupling Single Spins in Diamond,” D. D. Awschalom, Symposium on Diamond Electronics, Materials Research Society, Boston, MA, November 27 ˆ December 1, 2006.

109. “Imaging and Manipulating Single Spins in Diamond,” D. D. Awschalom, Frontiers in Optics, 90th Annual Optical Society of America Meeting, Laser Science XXII, Rochester, NY, October 8-12, 2006.

110. “Current-induced Polarization and the Spin Hall Effect in Semiconductors”, D. D. Awschalom, Gordon Research Conference on Magnetic Nanostructures, Oxford University, Oxford, UK, September 3-8, 2006.

111. “Imaging the Spin Hall Effect and Current-induced Spin Polarization in Semiconductors,” D.D. Awschalom, The 17th International Conference on Magnetism (ICM2006), Kyoto, Japan, August 20-25, 2006.

112. “Enhancement of Spin Coherence Using Q-factor Engineering in Semiconductor Microdisk Lasers,” S. Ghosh (and D. D. Awschalom), 17th International Conference on Magnetism, Kyoto, Japan, August 20-25, 2006.

113. “Spin Manipulations in Semiconductors,” D.D. Awschalom, Plenary Talk, Fourth International Conference on the Physics and Applications of Spins in Semiconductors (PASPS-IV), Sendai, Japan, August 15-18, 2006.

114. “Generating and Manipulating Spins in Semiconductors,” D. D. Awschalom, Plenary Lecture, International Conference on Nanoscience + Technology, Basel, Switzerland, August 2006.

115. “Imaging the Spin Hall Effect and Current-induced Polarization in Two-dimensional Electron Gases,” V. Sih (and D.D. Awschalom), 28th International Conference on the Physics of Semiconductors, Vienna, Austria, July 24-28, 2006.

116. “Manipulation of Spins in Semiconductors,” D. D. Awschalom, Invited Lecture, Special Symposium on Spin Injection and Transport in Magnetoelectronics, CIMTEC Conference, 11th International Conference on Modern Materials and Technologies, Acireale, Sicily, Italy, 2006.

117. “Manipulating Spins and Coherence in Semiconductors,” D. D. Awschalom, Spins in Solids Summer School, Charlottesville, VA, June 18-23, 2006.

118. “Spin Hall Effect,” V. Sih (and D. D. Awschalom), Gordon Research Conference on Correlated Electron Systems, Mount Holyoke College, South Hadley, MA, June 18-23, 2006.

119. “Generating and Manipulating Spins in Semiconductors,” and “Controlling Spin Coherence with Semiconductor Nanostructures,” D. D. Awschalom, School and Workshop on Spin and Charge Effects at the Nanoscale, Scuola Normale Superiore, Pisa, Italy, June 1-9, 2006.

120. “Manipulating Quantum Information with Semiconductor Spintronics,” D. D. Awschalom, Physics Colloquium, Scuola Normale Superiore, Pisa, Italy, May 31, 2006.

121. “Generating and Manipulating Spinsin Semiconductors,” and “Controlling Spin Coherence with Semiconductor Nanostructures,” D. D. Awschalom, Keynote Speaker, International Conference on Quantum Spin Transport in Solids, Institute of Advanced Studies, Nanyang Technological University, Singapore, May 8-12, 2006.

122. “Spatial Imaging of the Spin Hall Effect and Current-induced Polarization in Two-dimensional Electron Gases,” V. Sih (and D.D. Awschalom), March Meeting of the American Physical Society, Baltimore, MD, March 13-17, 2006.

123. “Imaging the Spin Hall Effect and Current-induced Polarization in Two-dimensional Electron Gases,” D.D. Awschalom, International Symposium onMesoscopic Superconductivity and Spintronics (MS+S2006), NTT Basic Research Laboratories, Atsugi-shi, Japan, February 27-March 2, 2006.

124. “Spin Manipulation in Semiconductors,” D. D. Awschalom, Gordon Research Conference on Ultrafast Phenomena in Cooperative Systems, Buellton, CA, February 9, 2006.

125. “Optoelectronic Control of Spin Exchange Interactions in Magnetic Semiconductor Heterostructures,” R.C. Myers (and D.D. Awschalom), Gordon Conference on Ultrafast Phenomena in Cooperative Systems, Buellton, CA, February 5-10, 2006.

126. “Manipulating Quantum Information with Semiconductor Spintronics”, D. D. Awschalom, Frontiers in Physics Symposium, American Institute of Physics Forum on Industrial Physics for Corporate and Academic Leaders, National Institute of Standards and Technology (NIST), Gaithersburg, MD, November 8, 2005.

127. “Current-induced Polarization and the Spin-Hall Effect in Semiconductors,” D. D. Awschalom, 50th Annual Conference on Magnetism and Magnetic Materials, San Jose, CA, October 30 ˆ November 3, 2005.

128. “Spintronics: Semiconductors, Molecules, and Quantum Information Processing,” D. D. Awschalom, Whitfield Lecture, Pennsylvania

State University, University Park, PA, September 29, 2005..

129. “Manipulating Quantum Information with Semiconductor Spintronics,” D. D. Awschalom, International Symposium on Foundations of Quantum Mechanics in the Light of New Technology (ISQM), Hatoyama, Saitama, Japan, August 22-25, 2005.

130. “Current Induced Polarization and the Spin Hall Effect in Semiconductors,” Y. Kato (and D. D. Awschalom), 24th International Conference on Low Temperature Physics, Orlando, FL, August 10-17, 2005.

131. “Current-induced Polarization and the Spin Hall Effect in Semiconductors,” Y. Kato (and D. Awschalom), Third International Conference on Spintronics and Quantum Information Technology (Spintech III), Awaji, Hyogo, Japan, August 1-5, 2005.

132. “Semiconductor Spintronics: Introduction and Overview,” D. D. Awschalom, Third International Conference on Spintronics and Quantum Information Technology (Spintech III), Awaji, Hyogo, Japan, August 1-5, 2005.

133. “Spin Torque Effects in Magnetic Nanostructures,” R. A. Buhrman, Workshop on Exploratory Nanospintronics, Wegberg-Wildenrath, Germany, Oct. 28-30, 2005

134. “Spin-based quantum computation in semiconductors”, M. E. Flatté, Spin and Charge Effects at the Nanoscale (SCEN06), Pisa, Italy, June 3, 2006. (invited)

135. “Optospintronics: open theoretical issues”, M. E. Flatté, KITP Spintronics Conference, Santa Barbara, California, March 20-24, 2006. (invited)

136. “Theory of magnetic circular dichroism in GaMnAs”, J.-M. Tang and M. E. Flatté, March Meeting of the American Physical Society, Baltimore, MD, March 14, 2006.

137. “Strong interactions between a nanomagnet and a microcavity mode”, O. O. Soykal and M. E. Flatté, March Meeting of the American Physical Society, Baltimore, MD, March 14, 2006.

138. “Theory of magnetic circular dichroism in GaMnAs”, J. M. Tang and M. E. Flatté, 52nd Midwest Solid State Physics Conference, Columbia, MO, October 8, 2005 (poster).

139. “Manipulating Nanomagnets Using Spin-Polarized Currents” D. C. Ralph Spin-Dependent Transport through Nanostructures – Spintronics '05, Sept. 25-30, 2005, Poznan, Poland

A. “Mechanically-Adjustable and Electrically-Gated Single-Molecule Transistors” C. Champagne, Invited Talk at the 2006 March Meeting of the American Physical Society, March 13-17, 2006, Baltimore, MD

140. “Magnetoresistance and Magnetic Dynamics on the Nanoscale” D. C. Ralph Spintronics Conference, March 20-24, 2006, Kavli Institute for Theoretical Physics, Santa Barbara, CA

141. "Magnetic Switching and Microwave-Frequency Precession Driven by Spin-Transfer Torques" D. C. Ralph, Conference on Spintronics Materials and Devices, May 19, 2006, Hitachi Global Storage Technologies, Almaden, CA

142. "Experiments on Magnetic Nanostructures" D. C. Ralph, Spintronics Program Seminar May 25, 2006, Kavli Institute for Theoretical Physics, Santa Barbara, CA

143. “Tools for Probing Electron and Spin Transport in Single Molecules” D. C. Ralph, 2006 Electronic Processes in Organic Materials Gordon Conference, Jul 30-Aug 4, 2006, Mount Holyoke College, MA

144. “Manipulating Nanomagnets Using Spin-Polarized Currents” D. C. Ralph 17th International Conference on Magnetism, Aug. 20-25, 2006, Kyoto, Japan

145. “Spin Transfer Studies in Magnetic Nanopillars and Nanoscale Magnetic Tunnel Junctions,” R. A. Buhrman, Invited talk, International Workshop on Spin Transfer, Nancy, France – Oct. 5-7, 2006.

146. “Oxygen Instabilities and the Electronic Properties of Oxide Tunnel Barrier Layers,” R. A. Buhrman, Invited Talk presented at 2006 APS March Meeting, Baltimore, Md., March 13-17, 2006.

147. “Spin transfer in nanoscale magnetic tunnel junctions,” G. Fuchs (and R. A. Buhrman,), Invited Talk presented at 2006 APS March Meeting, Baltimore, Md., March 13-17, 2006.

148. “Spin Torque and Dynamic Effects in Magnetic Nanostructures,” R. A. Buhrman, Tutorial presented at 2006 APS March Meeting, Baltimore, Md., March 13, 2006.

149. “Spin Torque and Magnetic Tunnel Junctions,” R. A. Buhrman , Spintronics Program Seminar May 25, 2006, Kavli Institute for Theoretical Physics, Santa Barbara, CA

150. “STM, XPS and Spin-Torque Studies of Magnetic Tunnel Junctions,” R. A. Buhrman, Invited Talk presented at Symposium Q - Magnetic Thin Films, Heterostructures, and Device Materials, MRS Spring 2006 Meeting, April 18 - 20, 2006.

Number of Presentations: 150.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. “Optical and Electronic Manipulation of Spin Coherence in Semiconductors,” V. Sih, E. Johnston-Halperin, and D. D. Awschalom, Invited Paper, Proceedings of the IEEE 91, 752 (2003).

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 1

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Kirill Bolotin	1.00
Vanessa Shi	1.00
R. Myers	1.00
Jay Stephens	1.00
R. Epstein	1.00
Dale Kitchen	1.00
Ozhan Ozatay	1.00
Nathan Emley	1.00
Jack Sankey	0.75
J. Berezovsky	0.75
F. Kuemmeth	0.75
Eric Ryan	0.75
P. Roushan	0.50
J. Pingenot	0.50
O. Soykal	0.50
A. Putilin	0.50
FTE Equivalent:	**13.00**
Total Number:	**16**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Ilya Krivorotov	0.10
Ronald Kawakami	0.10
Sau Ghosh	0.10
Wayne Lau	0.10
J. M. Tang	0.38
W. H. Lau	0.38
Radovan Urban	1.00
Abhay Pasupathy	1.00
Eyal Buks	0.10
Kamil Ekinci	0.10
Pritiraj Mohanty	0.10
FTE Equivalent:	**3.46**
Total Number:	**11**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert Buhrman	0.05	No
David Awschalom	0.05	No
Daniel Ralph	0.05	No
Michael Flatte	0.05	No
Michael Roukes	0.05	No
Ali Yazdani	0.05	No
FTE Equivalent:	**0.30**	
Total Number:	**6**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Kirill Bolotin
Ozhan Ozatay
Vanessa Shi
Jay Stephens
Richard Epstein
Dale Kitchen
Roberto Myers
Nathan Emley

Total Number: **8**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

1 a. Princeton University

1 b. Office of Sponsored Research Accountin
New South Building, Seventh Floor
Princeton NJ 08544

Sub Contractor Numbers (c): 39508-8012
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Research in spin dynamics and spin interactions in electronic nanostructues
Sub Contract Award Date (f-1): 8/1/2005 12:00:00AM
Sub Contract Est Completion Date(f-2): 8/31/2006 12:00:00AM

---

1 a. University of Illinois

1 b. Grants and Contracts Office
109 Coble Hall
Champaign IL 61820

Sub Contractor Numbers (c): 39508-6587
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Research on spin dynamics and spin interactions in electronic nanostructures
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 7/31/2005 12:00:00AM

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1 a. California Institute of Technology

1 b. Sponsored Research MC 201-15
California Institute of Technology
Pasadena CA 91125

Sub Contractor Numbers (c): 39508-6588
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Research on spin dynamics and spin interactions in electronic nanostructures
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 8/31/2006 12:00:00AM

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1 a. California Institute of Technology

1 b. Office of Sponsored Research
Mail Code 213-6
Pasadena CA 91125

Sub Contractor Numbers (c): 39508-6588
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Research on spin dynamics and spin interactions in electronic nanostructures
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 8/31/2006 12:00:00AM

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1 a. California Institute of Technology

1 b. Department of Applied Mathematics, 21'
1200 E. California Boulevard
Pasadena CA 91125

Sub Contractor Numbers (c): 39508-6588
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Research on spin dynamics and spin interactions in electronic nanostructures
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 8/31/2006 12:00:00AM

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1 a. University of California/Santa Barbara

1 b. Office of Research
3227 Cheadle Hall
Santa Barbara CA 93106

Sub Contractor Numbers (c): 39508-6587
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 8/31/2006 12:00:00AM

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1 a. Univesity of Iowa

1 b. Division of Sponsored Programs
2 Gilmore Hall
Iowa City IA 52242

Sub Contractor Numbers (c): 39508-6585
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Research on spin dynamics and spin interactions in electronic nanostructures
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 8/31/2006 12:00:00AM

Inventions (DD882)

5 **Bipolar Spin Transistors and Applications of the Same**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2):

5a: Michael Flatte

5f-1a: University of Iowa

5f-c: 2Gilmore Hall

Iowa City IA 52242

5a: Zhi Yu

5f-1a: University of Iowa

5f-c: 2 Gilmore Hall

Iowa City IA 52242

5a: David Awschalom

5f-1a: University of California, Santa Barbara

5f-c: 3227 Cheadle Hall

Santa Barbara CA 93106

5a: Ezekiel Johnston-Halperin

5f-1a: University of California, Santa Barbara

5f-c: 3227 Cheadle Hall

Santa Barbara CA 93106

(3) List of Appendixes, Illustrations and Tables - None

(4) Statement of Problem Studied

This interdisciplinary and multi-university MURI project had as its objective the understanding and control, at the nanoscale, of the *spin properties* of electronic systems of major technological potential. The project emphasized the study and investigation of spin-based effects in nanostructures fabricated by both bottom-up and top-down methods. In the former case, we assembled nanoscale systems, spin-by-spin, by both atomic manipulation and advanced materials processing techniques, to enable the detailed, systematic study of the fundamental properties of these spin structures by state-of-the-art scanned probe technologies. In the latter case, the most advanced methods of nanofabrication and materials growth and processing were employed to produce *functional* nanostructured *spin devices* that could be electronically addressed and studied by highly sensitive tunneling and direct electrical transport spectroscopies, and to form new types of *spintronic systems* that could be investigated in detail by advanced optoelectronic imaging techniques.

(5) Summary of the Most Important Results

During this MURI program major advances were accomplished in all three of the primary focus areas of the program:

(a) The development and application of new tools and innovative techniques for the manipulation and study of spin phenomena in semiconductor systems, and other spintronics materials of technological importance, and the spectroscopic study of the spin transport properties of nanoscale systems;

(b) The understanding, development and enhancement of methods for the excitation and switching of nanomagnets by spin-polarized currents;

(c) The development and application of innovative scanned probe instruments for a range of nanoscale and atomic scale studies of both few and many spin systems and of material systems of critical importance to spintronics applications.

Optical and electrical manipulation and study of spins in electronic systems

Understanding and controlling spin dynamics in semiconductor systems is essential for the realization of a range of future spintronic devices. Therefore a major initial focus of this multi-year MURI effort was on the successful development of new spatio-temporal magneto-optical imaging techniques for the control and study of spin dynamics in semiconductor structures. Subsequently, we employed these tools in the exploration of new pathways for all-electrical generation and manipulation of spin-based information using semiconductors and hybrid semiconductor/FM heterostructures. This also involved new spintronics materials development efforts including: (a) developing improved growth protocols for magnetically-doping GaAs to maintain clean electrical and optical properties; (b) engineering n-type III-V heterostructures and thin films for pioneering spin Hall experiments; and exploring and demonstrating the spintronics capabilities of n-type ZnO semiconductors and synthetic N-doped diamond films.

Spin dynamics and the spin-Hall effect: In an early application of our magneto-optical imaging capabilities we successfully used time-resolved Kerr rotation to demonstrate optical and electronic tuning of both electronic and local moment Mn2+ spin dynamics in electrically-gated parabolic single 7.5 nm quantum wells derived from diluted magnetic semiconductors. We found that by changing either the electrical bias or the laser energy, the electron spin precession frequency can be varied over a wide range, from 0.1 to ~1 THz. This corresponds to the electrical tuning of the effective electron g-factor over a range that is an order of magnitude larger than that which has been achieved with similar, but nonmagnetic, parabolic quantum well systems. Additionally, we successfully demonstrated that such structures allow the electrical modulation of the local moment dynamics in the solid state, which is manifested as changes in the amplitude and the lifetime of the optically observed Mn2+ spin precession under electrical bias.

We then turned to a research effort designed to examine and engineer the spin Hall effect in semiconductors, for the ultimate purpose of developing techniques for the electrical sourcing of tunable spin polarization and spin currents in non-magnetic semiconductor systems. The spin-Hall effect refers to the generation of a spin current transverse to a charge current in nonmagnetic systems in the absence of an applied magnetic field. Although spin current is difficult to measure directly, the spin-Hall effect can create spin accumulation at the edges of a channel. This electrically induced spin polarization was observed by our group in bulk epilayers of electron-doped semiconductors and in two-dimensional electron systems, and recent calculations showed reasonable agreement with the experimental results. However, determining the spin current through analysis of the spin accumulation is complicated because spin is not a conserved quantity in the presence of the spin-orbit interaction and the choice of boundary conditions has a strong effect on the calculated spin accumulation. In order to clarify the origin of the electrically induced spin polarization, we designed structures in which the effects of the boundary of the electric field were separated from edge effects. We fabricated mesas with transverse channels to allow spins to drift into regions in which there is minimal electric current. Using Kerr rotation microscopy, we were able to observe the generation of a transverse bulk electron spin current created by a longitudinal voltage, which can cause spins to drift nearly 40 microns into a transverse channel. In addition, we determined the spin drift velocity from the magnetic field dependence of the measured spin polarization.

We also investigated the spin Hall effect and current-induced spin polarization in a two-dimensional electron gas confined in (110) AlGaAs quantum wells using Kerr rotation microscopy. We found that the spin Hall profile shows complex structure and the current-induced spin polarization is out-of-plane. The experiments map the strong dependence of the current-induced spin polarization to the crystal axis along which the electric field is applied, reflecting the anisotropy of the spin-orbit interaction. Our results revealed new opportunities for tuning a spin source using quantum confinement and device engineering in non-magnetic materials. Spin-orbit engineering in two-dimensional systems allows for the manipulation of the magnitude and direction of the internal fields for sourcing spin polarization in non-magnetic semiconductors. Moreover, we showed that these interactions can be used to operate on electron spins by changing the direction of current, thereby enabling new degrees of control for quantum confined spintronic devices.

Optical studies of spin phenomena in new materials systems for spintronics applications: To establish a strong materials foundation for future spintronics applications, particularly those that will be applicable at room temperature and above requires a broad and aggressive investigation of the spin-based properties of a range of electronic materials systems that are now beginning to be grown and produced at a high level of quality. Recently a great deal of attention has been focused on ZnO because of material properties that make it well suited for applications in ultraviolet light emitters, transparent high power electronics and piezoelectric transducers. Theoretical work predicting room temperature ferromagnetism for Mn-doped ZnO has revealed the possibility that ZnO may be an appropriate candidate for spintronics. While the magnetic properties of thin films of ZnO are being widely investigated, practical spintronics applications would also require long spin coherence time and spin coherence length. Consequently as part of this MURI effort we investigate the electron spin dynamics of nonmagnetically doped n-type ZnO. We made measurements over a range of temperatures and magnetic fields, and found that spin coherence persists to room temperature in both bulk and thin film samples. Our measurements on n-type ZnO established a spin coherence time of ~190 ps at room temperature, longer than the spin coherence time reported in GaN, another wide-band-gap semiconductor. ZnO also has the added advantage that high-quality single crystals are commercially available, adding to the attractiveness of ZnO as a candidate material for spintronics.

Another promising and intriguing spintronics materials system is the nitrogen-vacancy (NV) center in diamond which is a candidate atomic-scale system for solid-state quantum information processing. Experiments have shown that N-V centre ensembles can have spin-coherence times exceeding 250 microseconds at room temperature. Consequently in this MURI project we developed an angle-resolved magneto-photoluminescence microscope apparatus to investigate the anisotropic electron-spin interactions of single N-V centers at room temperature. We observed negative peaks in the photoluminescence as a function of both magnetic-field magnitude and angle that are explained by coherent spin precession and anisotropic relaxation at spin-level anti-crossings. In addition, precise field alignment unmasks the resonant coupling to neighboring 'dark' nitrogen spins, otherwise undetected by photoluminescence. These results demonstrated the capability of our spectroscopic technique for measuring small numbers of dark spins by means of a single bright spin under ambient conditions. With higher purity samples and single-ion implantation, these results could make possible the long-range coupling of two individually addressable N-V centers connected by a chain of dark spins, enabling experimental tests of spin-lattice theories and quantum information processing schemes.

Spin properties of single and few quantum states: Our major achievements in this part of the overall MURI effort resulted from the development of an innovative new nanofabrication technique that allowed us to connect single molecules or single metal nanoparticles to source and drain electrodes in a transistor geometry, with a third gate electrode nearby that can be used to tune the charge on the nanostructure. This new technique enabled us to measure for the first time spin-polarized transport through single quantum states and how these states are affected by spin-dependent interactions. We first used this approach to study spin-orbit coupling, spin filtering by individual states, and how the Kondo effect for non-magnetic molecules is affected by contact with ferromagnetic electrodes. We then moved to investigate in detail the properties of bare atomic-scale magnetic contacts, in preparation for future studies of spin-dependent tunneling through single molecules. We found much larger variations in magnetoresistance from device to device in these simple point contacts than are seen in large devices. We also discovered a new effect in the point contacts, a greatly enhanced anisotropic magnetoresistance -- changes in resistance as the magnetization in the contact remains spatially uniform but is rotated relative to the current direction. We were able to identify both effects as due to a fundamental quantum interference phenomenon. The electron orbits in a ferromagnet are changed as the magnetization rotates, due to spin-orbit coupling, thereby causing the resistance to fluctuate due to variations in quantum interference. In this effort we also completed studies of electron transport through single magnetic molecules (Mn_{12} acetate) connected to non-magnetic electrodes. These measurements yielded clear signatures of tunneling via magnetic states, although further work will be needed to improve the degree of reproducibility.

STM spin manipulation and studies of individual spin-spin interactions

A signature accomplishment in this MURI project was the development and application of a unique, bottom-up STM technique for the study and manipulation of spin-based phenomena. With this technique we successfully studied single spins in well-defined situations and demonstrated that we can build up and study interacting spin assemblies, by adding one spin at a time. To accomplish this major advance we utilized the capabilities a state-of-the-art low temperature scanning tunneling microscope (STM) and developed new atomic-manipulation techniques. This work has resulted in the establishment of a new means to probe single spins and their interactions, and thus successfully demonstrated a new approach for the development of materials and probes suitable for quantum measurements and computing.

The materials system on which this effort was focused was transition metal impurities in gallium arsenide (GaAs) semiconductors, and was chosen as a model situation to probe the basic interactions that can give rise to magnetism in semiconductors. After developing a novel atom-by-atom substitution technique with the STM to controllably incorporate the transition metal dopants into GaAs we measured the electronic states of isolated single acceptors in an identical configuration—Ga sites in the top layer of a GaAs (110) surface. We determined the acceptor levels and anisotropic shape of the hole states for manganese, iron, cobalt, and zinc with STM topography and spectroscopy and determined that the manganese acceptor has a deeper acceptor level than the non-magnetic zinc acceptor. We also established that the iron and cobalt acceptors both have two acceptor levels that are complementary in their spatial distribution. We were able to establish the influence of the GaAs band structure and the p-d hybridization on the character of the hole states. In addition, we probed the Mn acceptor in n-type and p-type GaAs to understand the role of tip-induced band bending and surface in our experiments. We also showed that the acceptors probed at the GaAs (110) surface retain bulk-like characteristics and thus that our results are highly relevant to understanding hole-mediated ferromagnetic interactions.

A major achievement in this project was the first controlled atomic-scale study of the interactions between isolated Mn impurities mediated by electronic states in GaAs. High-resolution STM measurements provide visualization of the GaAs electronic states that participate in Mn-Mn interactions. The splitting of bonding/antibonding states of nearest-neighbor Mn-Mn pairs was directly observed revealing that that these Mn-Mn pairs are ferromagnetically aligned, which contradicts the expectations developed from ab initio calculations of Mn-Mn pairs via density functional theory. The experimental findings regarding the Mn-Mn pair interactions were successfully explained using tight-binding model calculations and both the experiment and the calculations demonstrated a strong dependence of ferromagnetic interaction on crystallographic orientation. In particular we found that the tight-binding model relates the acceptor level splitting with the spin-spin interaction energy J. This anisotropic interaction can potentially be exploited by growing oriented $Ga_{1-x}Mn_xAs$ structures to enhance the ferromagnetic transition temperature beyond that achieved in randomly doped samples.

We have also shown theoretically that even in the absence of any magnetic fields we can use electric fields to split the energy levels of the Mn impurity state as well as manipulate the states coherently. We have calculated the splitting energies and the state-to-state coupling. The resulting Rabi flopping times are about 80 picoseconds, which are much shorter than the 500 picosecond lower bound on the experimental spin coherence time of these complexes (measured with ESR on ensembles). Thus all-electrical ESR on these individual Mn states should be possible by determining the orientation of the pseudospin of the Mn state through measurement of the bias dependence of the tunneling current from the STM tip.

Magnetism at the Nanoscale

Of the many important results and major advances obtained in this MURI project, the one with perhaps the greatest potential for near-term technological impact was the demonstration that spin-polarized electrical currents can be used to manipulate the orientation of the moments in nanoscale magnetic devices, through a "spin-transfer" or “spin-torque” mechanism that can be much more efficient than using magnetic fields. Our work in this area was focused on understanding the fundamental science of spin-transfer-driven magnetic dynamics, so as to provide the scientific foundation for spin-transfer magnetic memory elements and high-quality-factor variable frequency GHz oscillators. Through a series of investigations we demonstrated what the mechanism of interaction between a magnet and a spin-polarized current is that gives rise to a torque on a nanomagnet, and we developed new experimental techniques for measuring how nanomagnets respond to these torques. Building on these initial advances we made significant progress toward applying these discoveries for uses in non-volatile magnetic memories and high-frequency signal-processing devices.

At the beginning of this project our work showed that the dominant mechanism behind the spin-transfer torque was the absorption of angular momentum transverse to the moment of a magnetic element, rather than an alternative “effective field” mechanism that had been proposed. We clarified the role of thermal fluctuations on spin-transfer-driven magnetic switching. We developed the first techniques by which the dynamics of a single nanomagnet can by measured directly, and used these techniques to make measurements of spin-transfer-driven magnetic dynammics in both the frequency and time domains. Using these techniques we were able to map the phase diagram as a function of current and applied magnetic field for the different possible dynamical modes of a nanomagnet. In addition, we showed that spin-transfer excitations were possible in magnetic tunnel junctions as well as all-metal spin valves, thereby achieving devices with the impedance levels that are appropriate for back-end-of-the-line integration with Si electronics for high performance on-chip magnetic memory applications.

Most recently we made advances in several strategies for reducing the magnitude of the current needed to generate spin-transfer-driven magnetic reversal in memory devices. These include optimizing the size and shape of the moving magnetic element, and injecting the current through the device in a spatially non-uniform manner, so as to generate a small reversed domain that sweeps through the device. We also determined that our devices are likely affected by a layer of oxidation along their edges that increases the magnetic damping. Developing a fabrication procedure that avoids this increased damping should provide another route to decrease critical currents.

Finally, in another major advance during the last year of this project, we developed a technique for performing ferromagnetic resonance measurements on single nanomagnets by using spin transfer from AC currents to resonantly excite magnetic precession. By sweeping the frequency of the excitation, we can separately excite the different normal modes of a nanomagnet, including both approximately uniform and spatially-nonuniform modes. By comparing frequencies, this allows us to determine the nature of the subset of modes that are driven into precession by an applied DC current. The widths of the resonances provide a direct means of measuring the magnetic damping, the crucial parameter in determining the switching current in these devices.

Scanned Probe Development and Studies of Spin Dynamics and Spintronic Materials

Ferromagnetic Resonance Force Microscopy (FMRFM): FMRFM is a variation of MRFM that enables characterization of dynamic magnetic properties of ferromagnetic thin films and multilayers at the micron scale. During the course of this program we developed this technique and, as a demonstration, employed it to investigate magnetostatic modes of yttrium iron garnet (YIG). A "probe" magnet at the tip of a compliant cantilever was used to introduce a local inhomogeneity in the internal field of the YIG film. This influenced the shape of the sample's magnetostatic modes, thereby measurably perturbing the strength of the force coupled to the cantilever. We developed a theoretical model based on the Landau-Lifshitz-Gilbert equation of motion and Maxwell's equations that explains these observations; it shows that tip-induced variation of the internal field created either a local "potential barrier" or "potential well" for the magnetostatic waves. The data and model together indicated that local magnetic imaging of ferromagnets is possible, even in the presence of long-range spin coupling, through the induction of localized magnetostatic modes predicted to arise from sufficiently strong tip fields. This makes FMRFM a unique experimental method allowing the investigation of local magnetic properties of the ferromagnetic samples independent of the sample dimensions, shape and/or defects at the sample edge. Incorporation of advanced nanomagnetic probe tips should enable next-generation FMRFM systems capable of imaging local magnetic properties with sub-micron lateral resolution.

An important focus of this effort was the development of nanomechanical resonators and cantilevel probes for investigations of spintronics materials and for applications in MFM/MRFM measurements. This work included the development of nanomechanical resonanter patterned from magnetic materials which has resulted in the first measurements of magnetostriction coefficients in a dilute magnetic semiconductor GaMnAs. We found that the resonance frequency shifts induced by field-dependent magnetoelastic stress could be used to simultaneously map the magnetostriction and magnetic anisotropy constants over a wide range of temperatures. Owing to the central role of carriers in controlling ferromagnetic interactions in this first material investigated, the results provided insight into a unique form of magnetoelastic behavior mediated by holes and should be applicable to a broad range of metallic and semiconducting magnetic materials.

We also successfully developed a new ultrasensitive piezoresistive cantilever approach for motion transduction that provides low power dissipation, provides high sensitivity, and is compatible with cryogenic, ultrahigh vacuum systems. This piezoresistive sensor is an enabling advance for the UHV cryogenic MRFM system that is under development at Cal Tech. The resonance frequency of this cantilever sensor is monitored by a custom made phase-locked-loop (PLL) which provides a maximum bandwidth of 1kHz with the maximum frequency resolution of 2mHz. Since this is an electrically-based detection scheme, this approach circumvents many difficulties inherent with making transport measurements in the presence of optical illumination (typically used to interrogate the cantilever in MFM/MRFM detector schemes).

Scanning tunneling spectroscopy, ballistic electron microscopy and X-ray photoemission studies of spin transport and spintronic materials: The spin filtering of STM-injected ballistic electrons by a thin ferromagnetic layer provides a powerful means for both studying spin-dependent ballistic-electron transport in electronic thin-film nanostructures and for imaging the magnetic behavior of ferromagnetic nanostructures with nanoscale resolution. During this MURI project we employed this STM technique to examine spin-dependent ballistic electron transport across epitaxial ferromagnet-semiconductor (F-S) interfaces, and also to use scanning tunneling spectroscopy, along with X-ray photoemission spectroscopy to study the electronic structure and chemical composition of the ultra-thin tunnel barriers, AlOx and MgO, that are currently essential to spin-injection and magnetic tunnel junction aspects of spintronics.

In the former case, we focused on examining spin dependent ballistic transport through epitaxal Schottky barrier interfaces formed by the MBE growth of Fe (001) on GaAs (001) substrates. By examining the bias dependence of the ballistic transport of hot electrons across the epitaxial interface we have established that the interface transmission probability is dependent upon the transverse momentum component of the incident electron and the degree to which it matches the requirement of the band structure of the GasAs collector. Because scattering both within the Fe base layer and at the Fe-GaAs interface can alter the momentum distribution of the tunnel-injected electrons, this provides a nanoscopic probe of the electronic and structural quality of the interface and epitaxial Fe layer. We found that even interfaces which exhibit very good quality factors as determined by I-V measurements on bulk diodes have inhomogenities at the nanoscale that reveal new information regarding the quality of the interfaces. This indicates steps that can be taken to enhance diode quality and spin injection efficiency and provided significant insights for the design and fabrication of improved hot-electron spin-injection structures and spin transistors.

In our tunnel barrier studies we undertook extensive investigations of ultra-thin insulator layers formed by both room temperature thermal oxidation (AlOx), and by room temperature epitaxial or textured growth on ferromagnetic electrode layers (MgO(001) on Fe(001) and on amorphous CoFeB.) Both of these material systems are widely employed as tunnel barriers in spin-injection and magnetic tunnel junction (MTJ) application. Through combined STS/BEEM and XPS studies, we have definitively determined that AlOx barrier layers, as formed, are substantially oxygen deficient and are also overcoated with a very significant layer of strongly chemisorbed oxygen. A key to the quality of the barrier layer is what happens to the chemisorbed oxygen when the oxide layer is over-coated by the top metallic electrode. In general, this oxygen is driven into the oxide filling vacancy sites or the oxygen can react with the top electrode. Those vacancies that remain can form leakage channels through the oxide reducing the tunnel magnetoresistance of the layer, while the oxygen that moves into the vacancy sites is often only weakly bound oxygen ions and thus can be a source of $1/f$ noise arising from fluctuations in their position. While we demonstrated that oxygen vacancies and instabilities are endemic in AlOx tunnel barrier layers, we also successfully developed growth protocols and post-growth processing techniques that greatly reduce their density and enhance the stability of the final tunnel barrier system.

In the case of the MgO tunnel barrier system our focus has been on such barriers as formed on CoFeB electrodes by the rf sputtering process which has been shown to yield the highest tunneling magnetoresistance (TMR) yet reported. Through our XPS and STM studies we found that this is a very rich system, particularly because rf sputtering of the barrier layer from an MgO target invariably evolves O ions that result in oxidation of the ferromagnetic electrode. The key then is what happens to this adventitious oxide during the MTJ processing, in particular what happens during the annealing cycle. We found that upon annealing, which generally acts to increase TMR, the Fe and Co oxides are reduced while the B oxide component increases and moves into the bulk of the MgO layer. The final amount of BOx that is formed and the degree to which the Fe and Co oxides are reduced or eliminated depends sharply on the precise details of the barrier formation process. This work revealed why the tuning of the barrier formation process is critical to obtaining high TMR with MgO barrier layers and pointed the way to magnetic tunnel junction fabrication procedures and processes can be expected to result in ultra-thin tunnel barriers with improved properties for important spintronic applications.

(9) Bibliography – NONE

(10) Appendixes – NONE